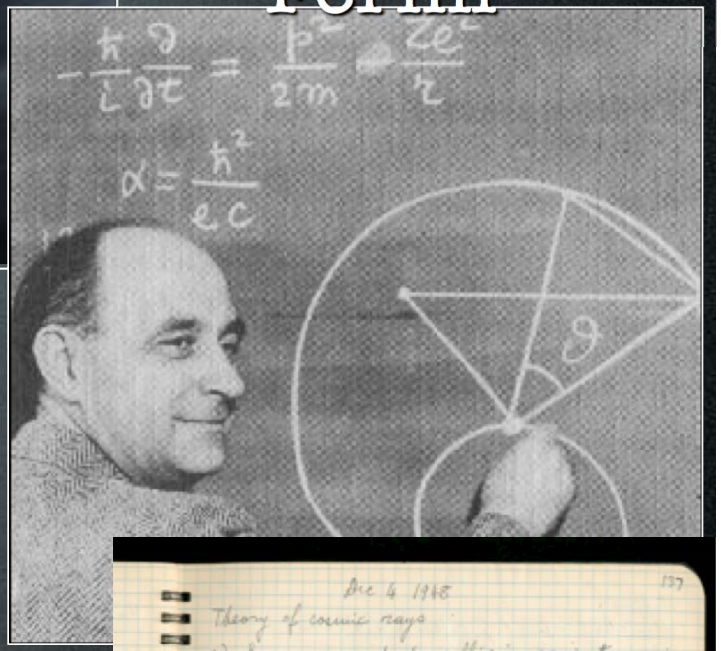
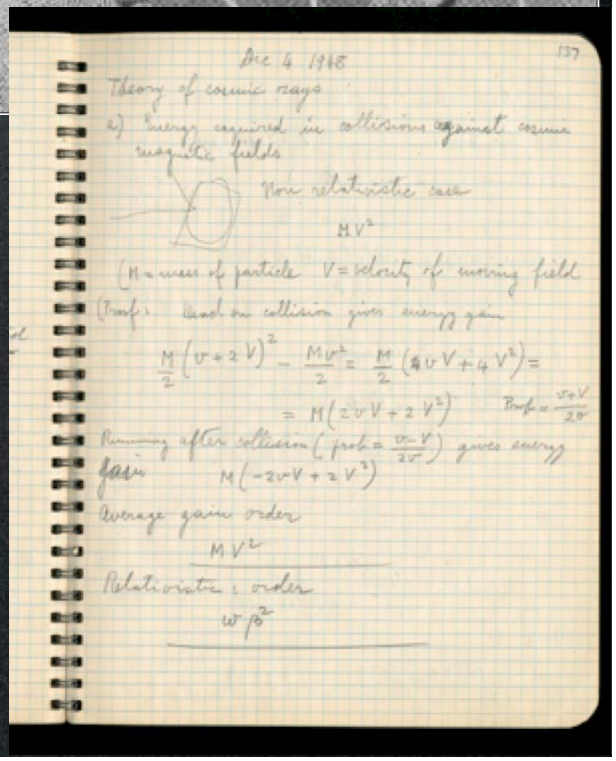
High-energy observations of Supernova remnants

Stefan Funk - Kavli Institute for Particle Astrophysics and Cosmology

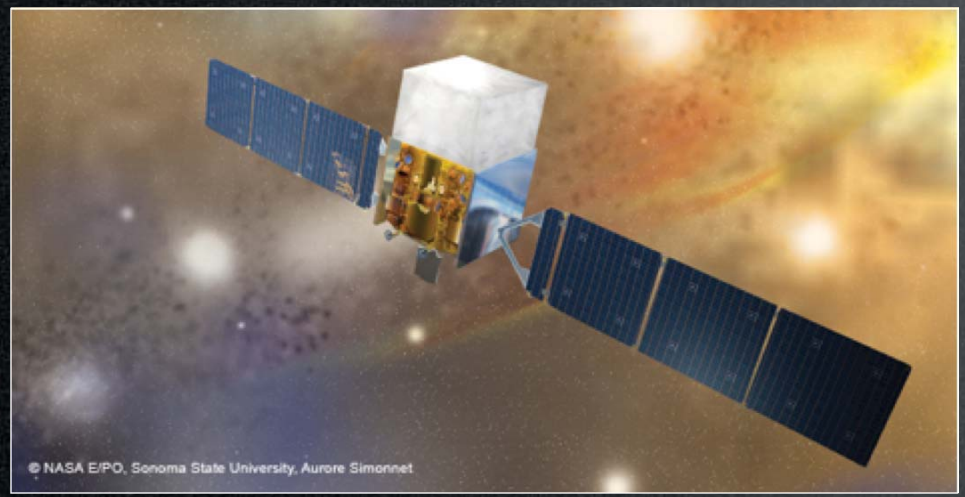
1912 Victor Hess

1949 Enrico Fermi

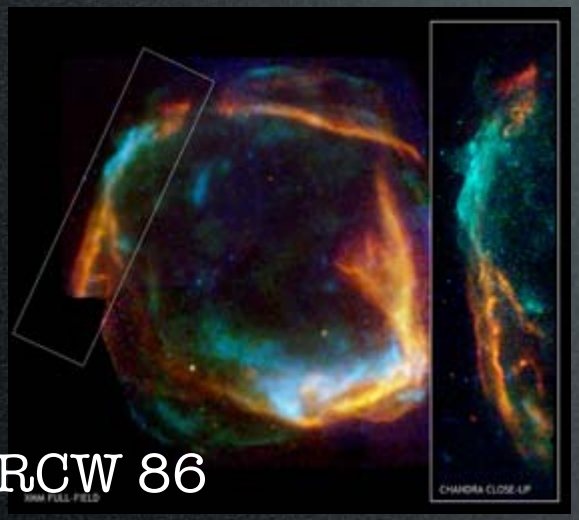




2012 Fermi Large Area Telescope



The best candidates



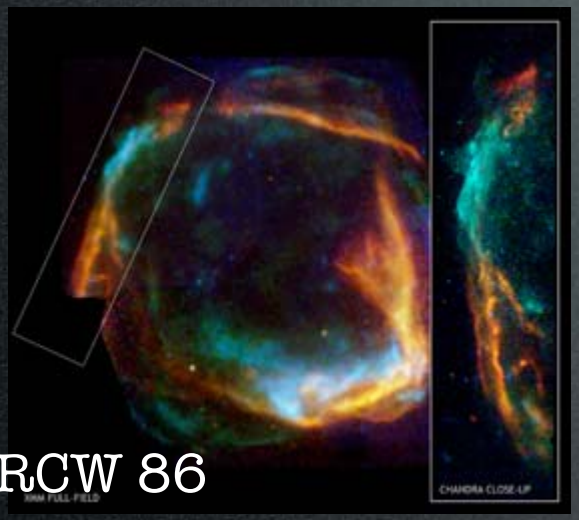
RCW 86


SN 1006


Cassiopeia A

- Cosmic particle accelerators (X-ray synchrotron suggesting 100 TeV e^-)
- Prime candidate for Proton acceleration to the knee
  - Energetics: 10% of kinetic energy of SN would suffice
  - Diffusive shock acceleration (prediction: power-law in energy)

The best candidates

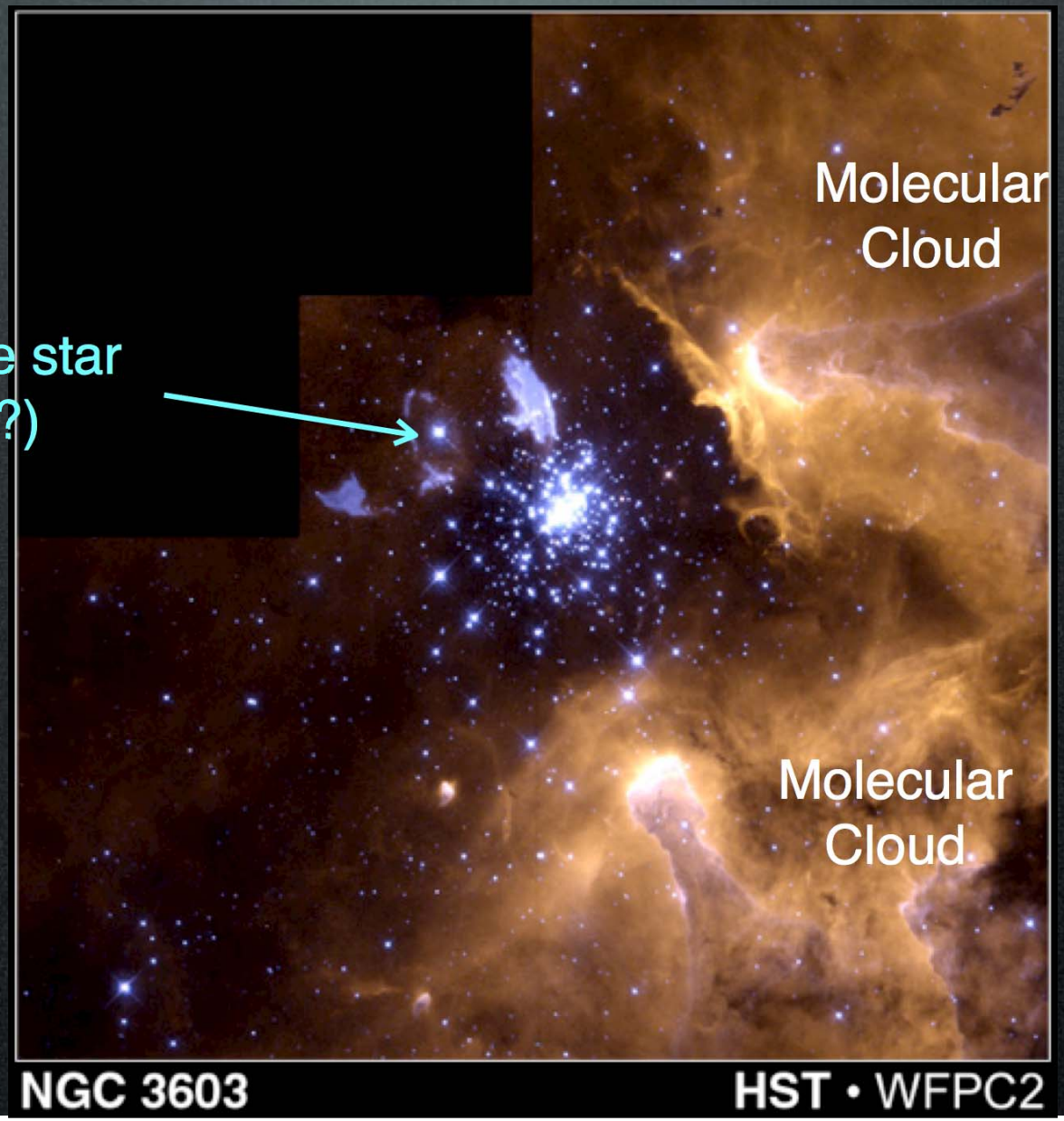


1) Do shell-type SNRs accelerate protons
2) Do they accelerate to the knee (10^{15} eV)?
3) What fraction of explosion energy is converted to accelerated particles

ce

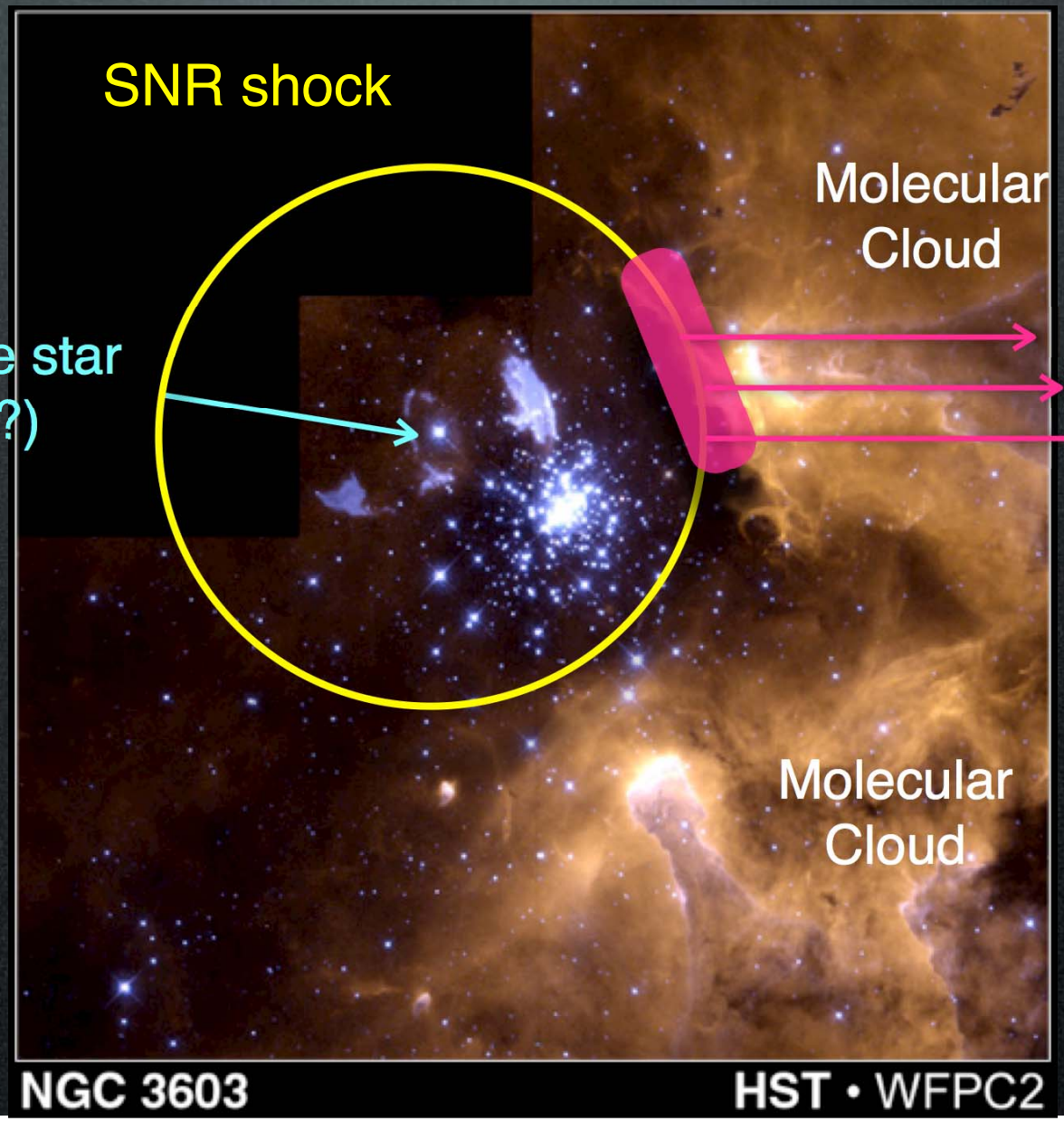
- Diffusive shock acceleration (prediction: power-law in energy)

The General Idea



Evolved massive star (about to die?)

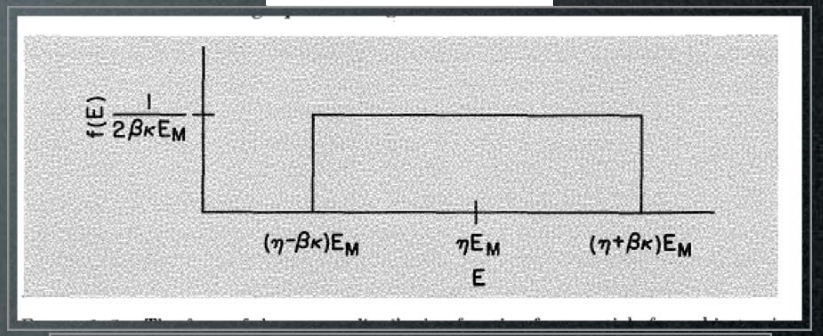
The General Idea



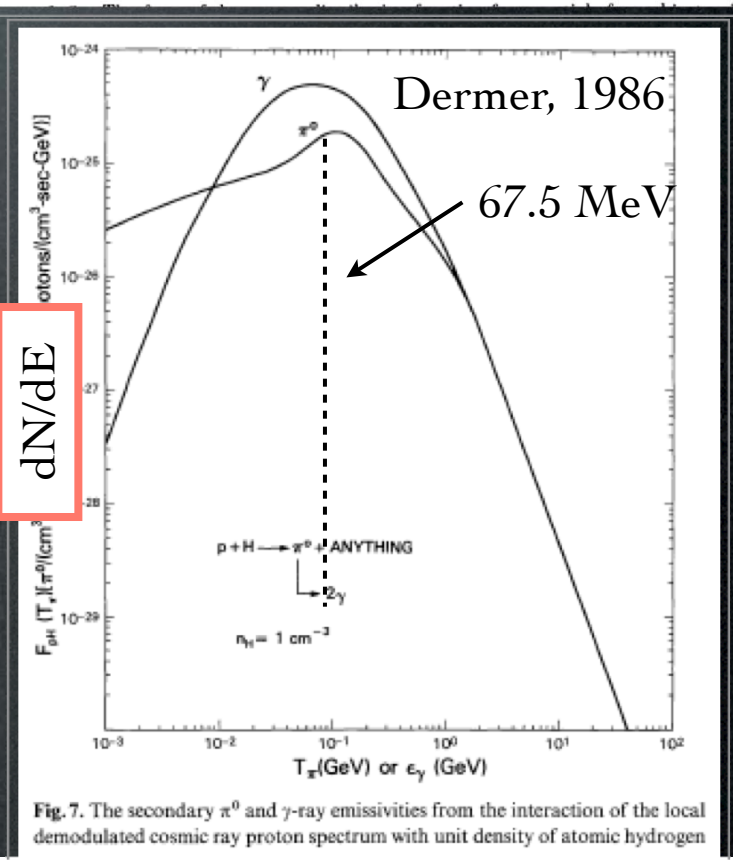
The π^0-decay bump

- Neutral pion-decay: in the rest-frame of the pion, the two γ rays have 67.5 MeV each (i.e. a line)
- Transforming into the lab-frame smears the line but keeps it symmetric about 67.5 MeV (in dN/dE)
- Transforming to E^2 dN/dE destroys symmetry and generates the "bump"

Stecker, 1971



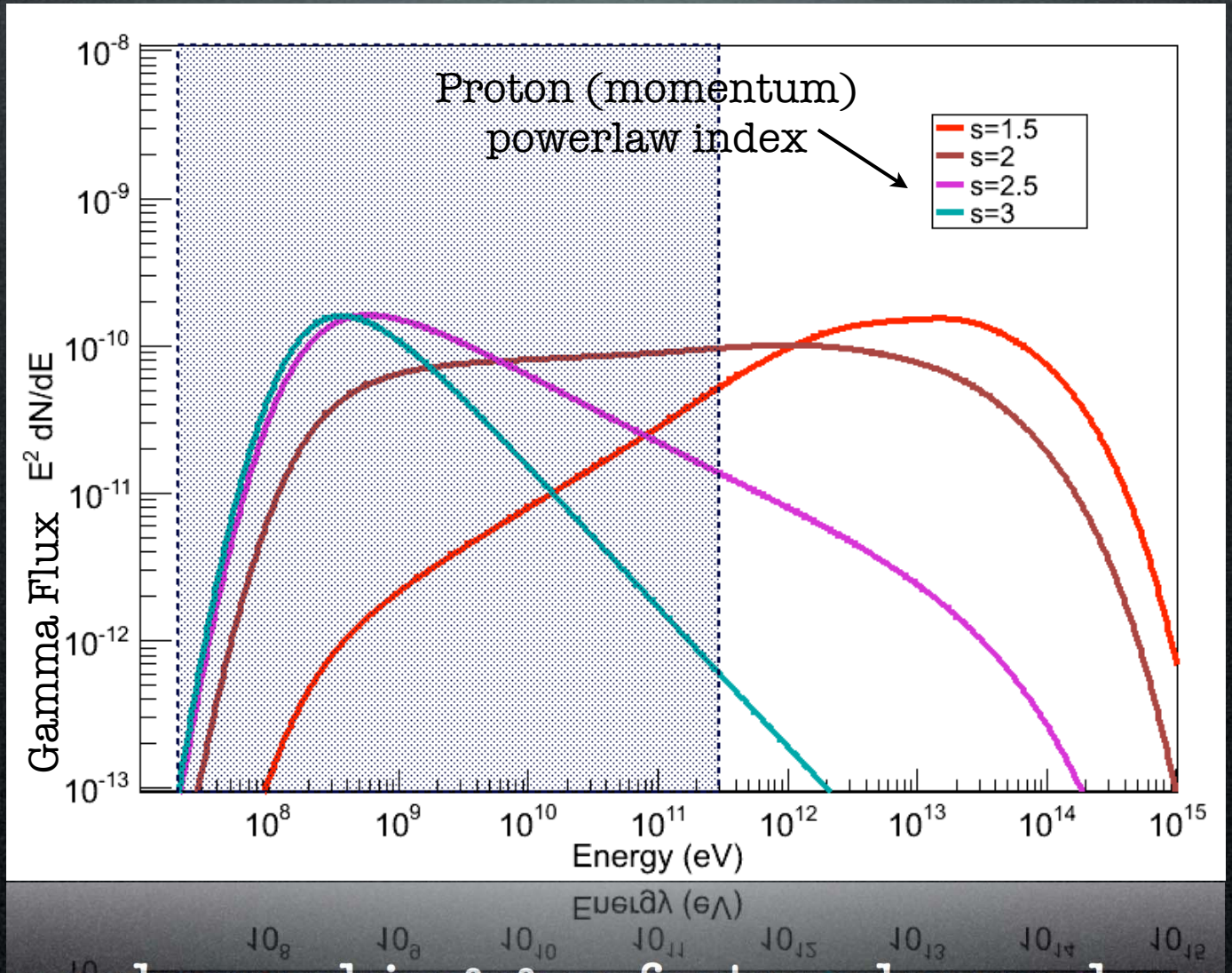
Dermer, 1986



dN/dE

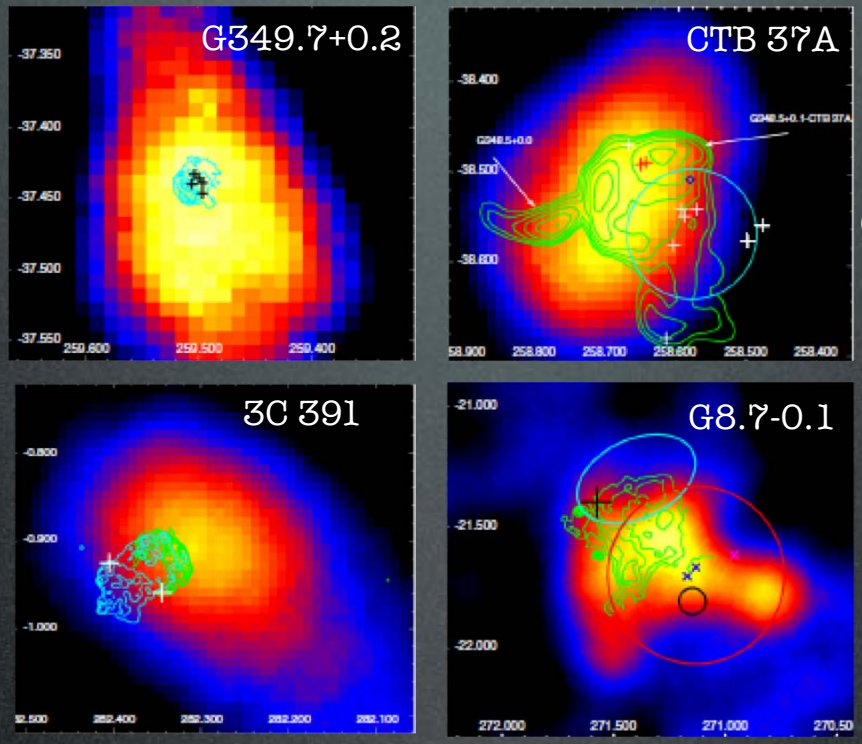
Fig. 7. The secondary π^0 and γ-ray emissivities from the interaction of the local demodulated cosmic ray proton spectrum with unit density of atomic hydrogen

The π^0-decay bump



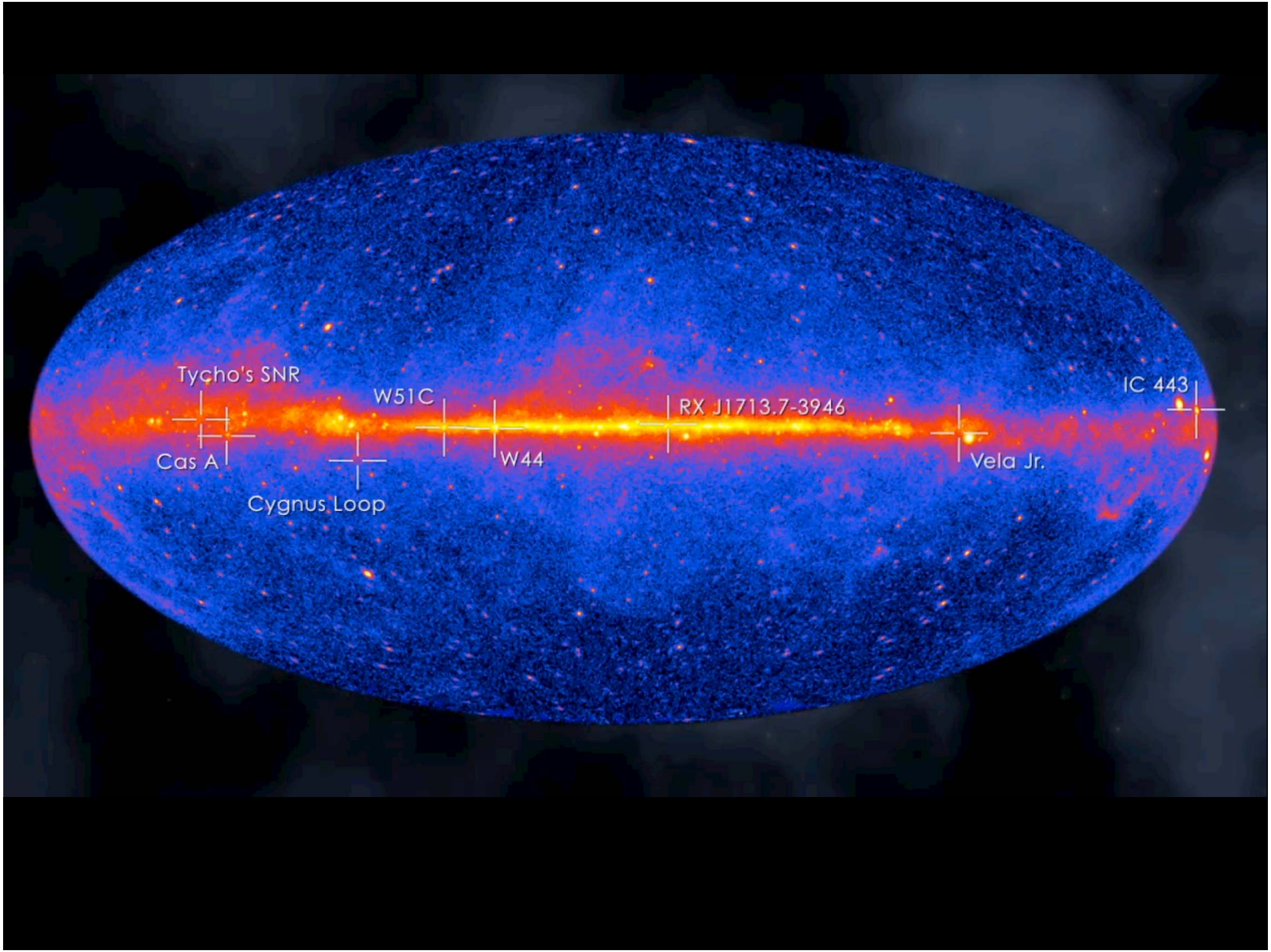
- The only smoking gun feature beyond neutrinos

Early indications

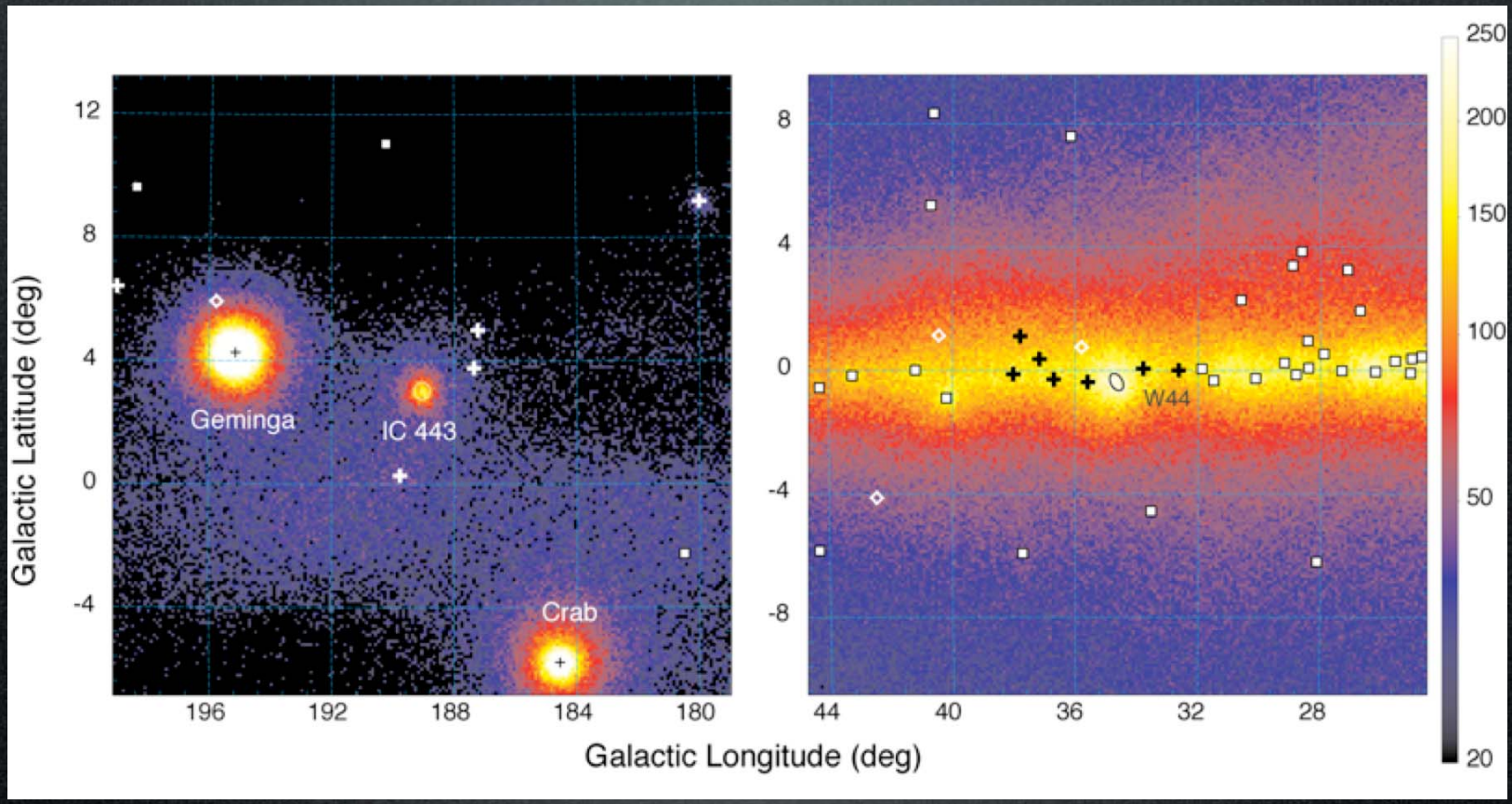


Castro&Slane 2010

- Detection of SNRs interacting with molecular clouds (maser emission)

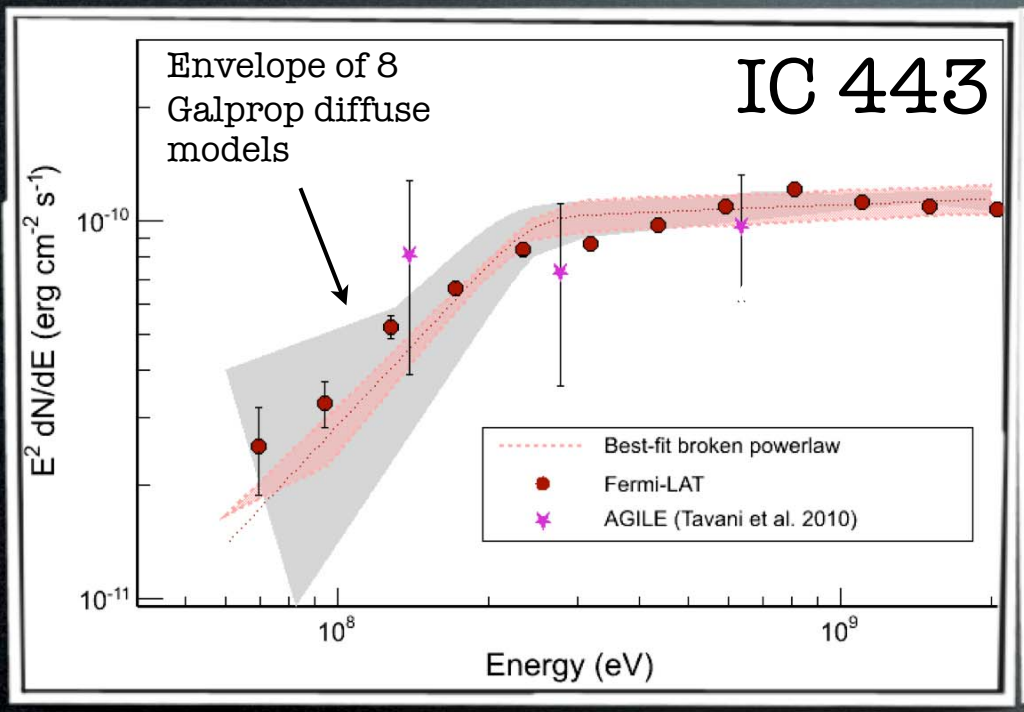

Tycho's SNR
W51C
RX J1713.7-3946
IC 443
Cas A
W44
Vela Jr.
Cygnus Loop

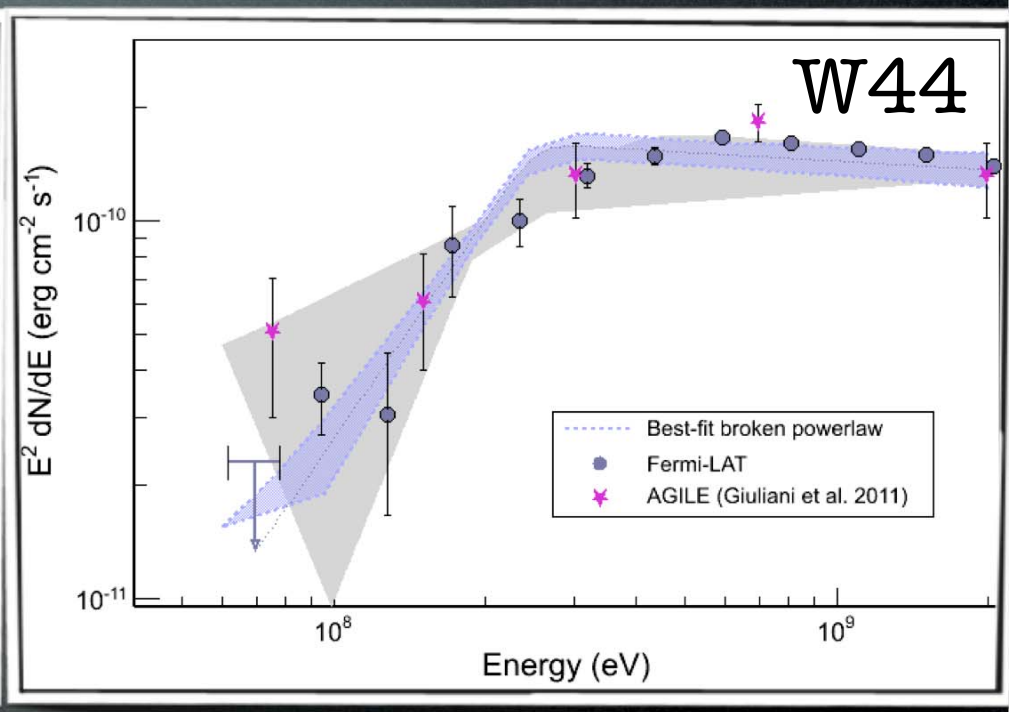
The best candidates



- IC 443 and W44 are the two brightest SNRs in the Fermi-LAT range

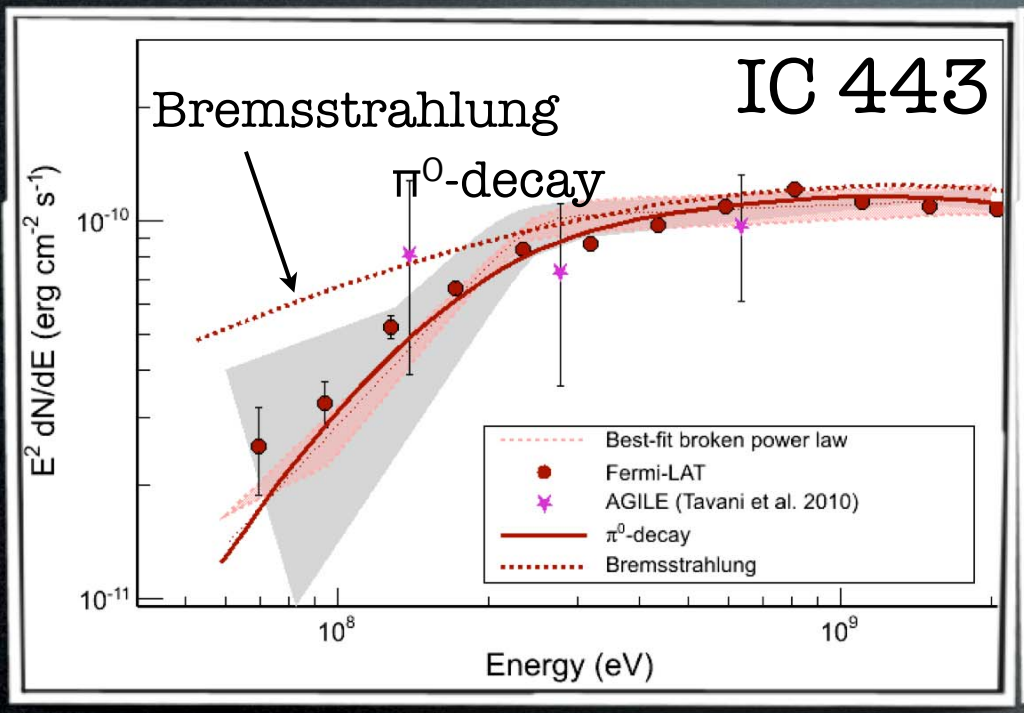
Clear detection of pion-bump

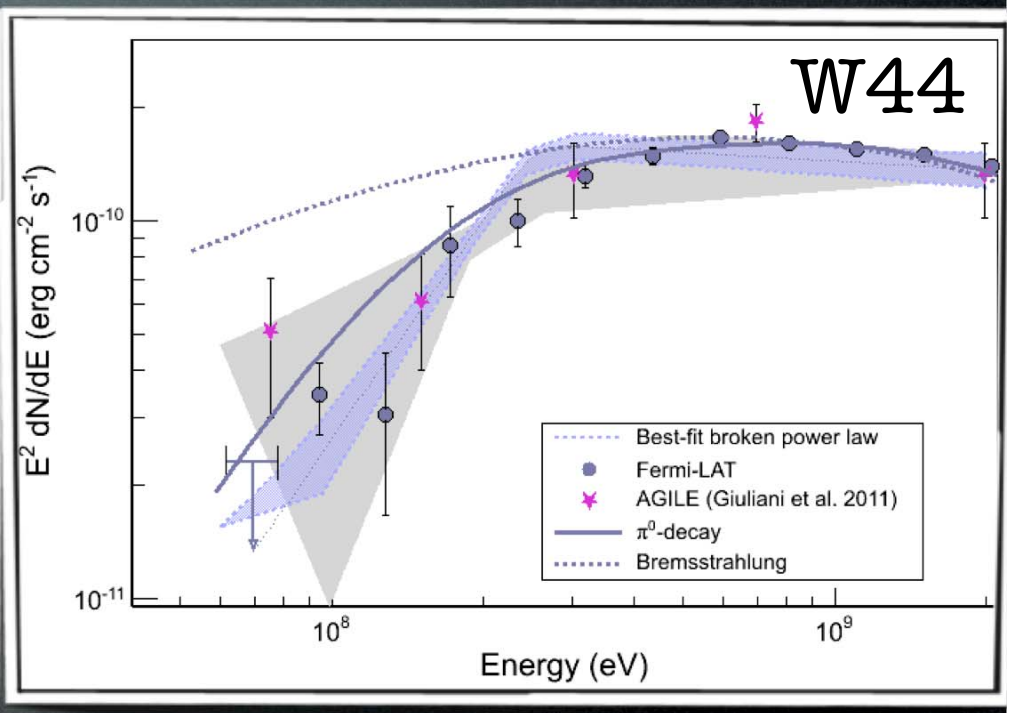




- Clear indication of a low-energy “turnover”

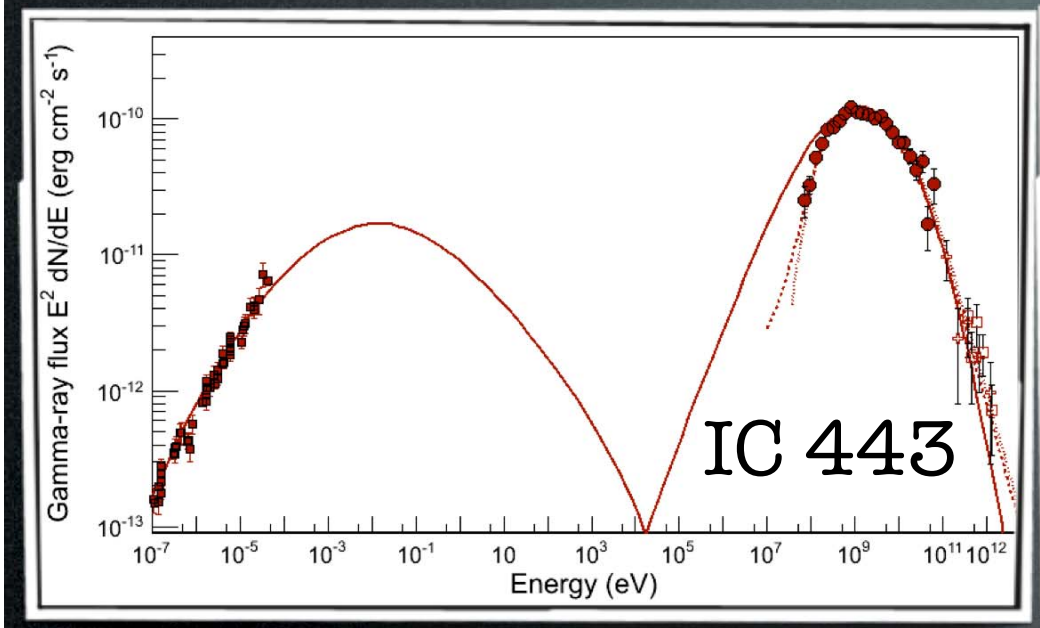
Clear detection of pion-bump

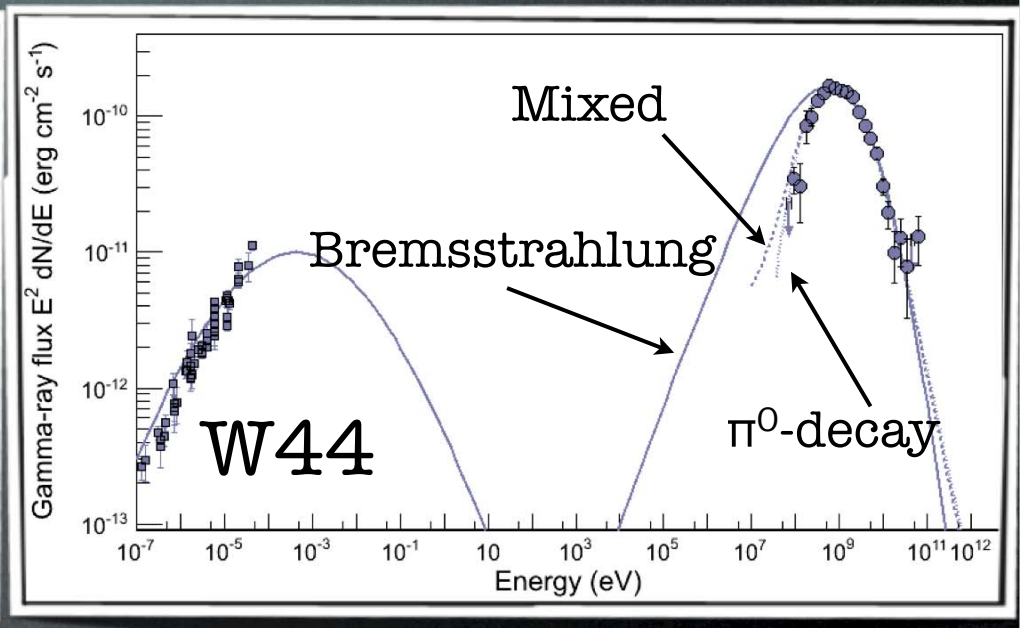




- Turnover matches what is expected from pion-decay
- Best-fit Bremsstrahlung model shows less steep decline

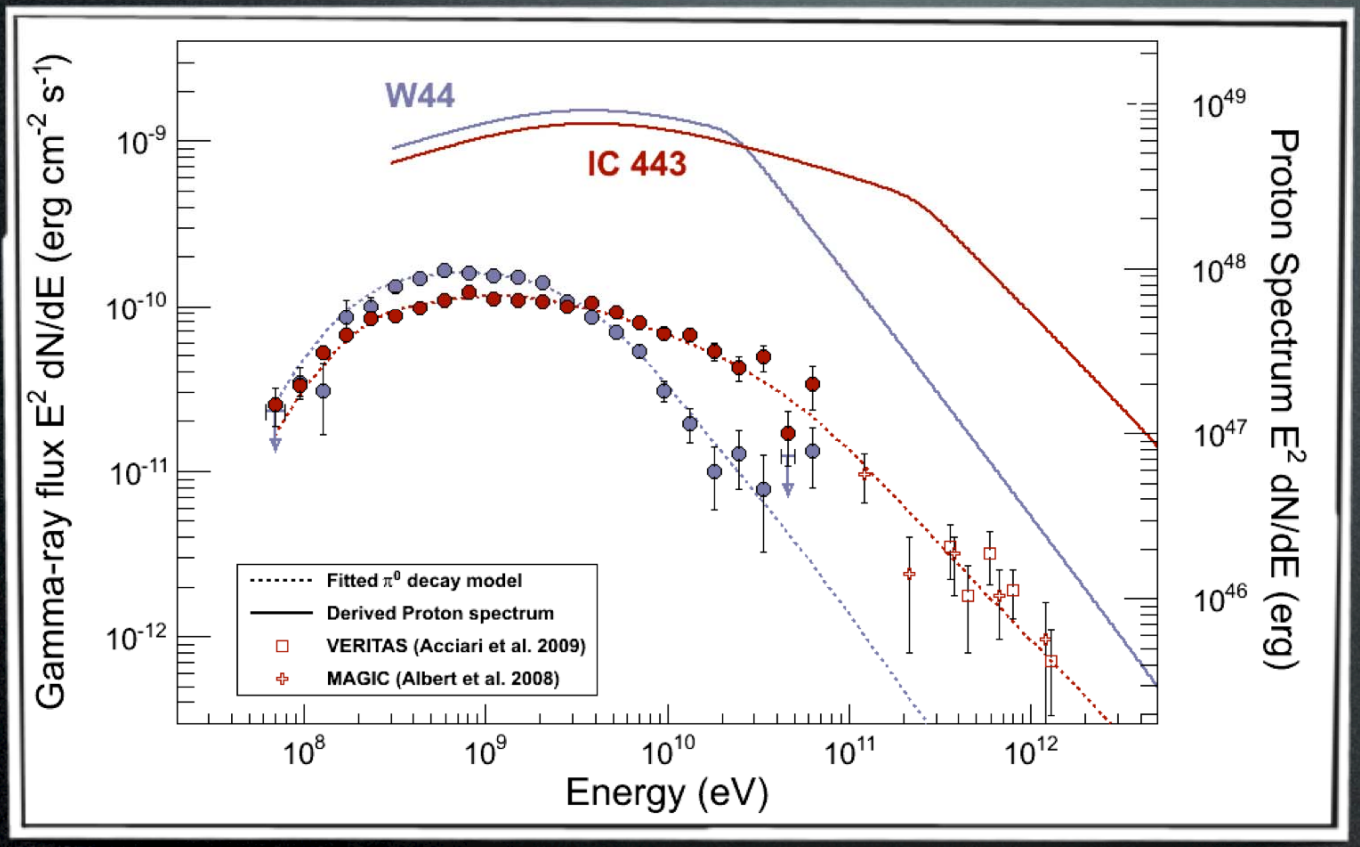
Ruling out leptonic scenarios





- Inverse Compton scenario: energetically completely disfavored (need factor 100 higher radiation fields). Also shape not consistent with IC
- Bremsstrahlung (solid): adjust B-field, total number of electrons and density to match observed emission. Spectra < 200 MeV inconsistent.
- Mixed model: Ratio electrons/protons: K_{ep}= 0.01 (dN/dp @ p=1GeVc^{-1})

Resulting Proton spectrum

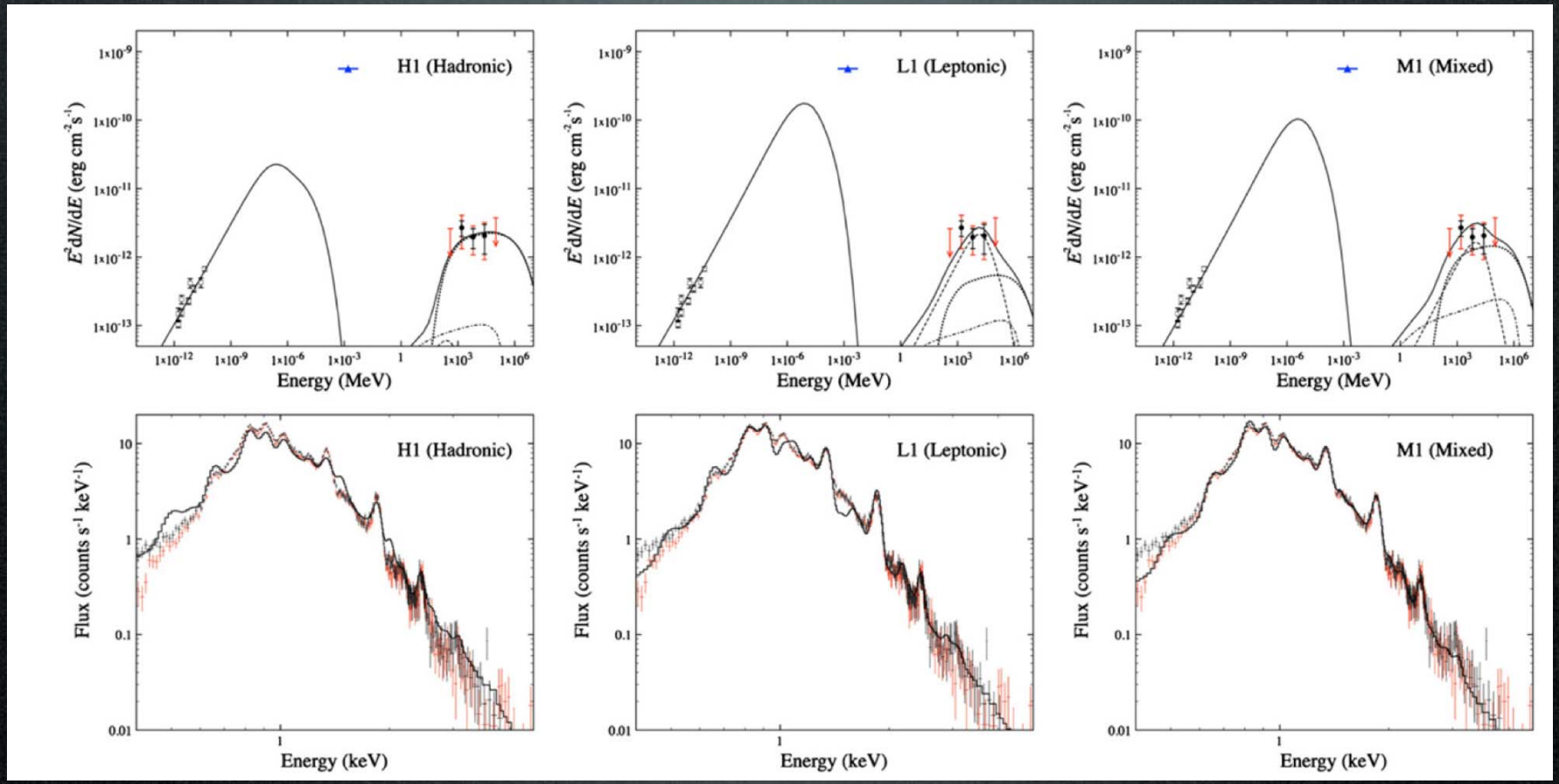


$$\frac{dN_p}{dp} \propto p^{-s_1}\left[1+\left(\frac{p}{p_{\rm br}}\right)^{\frac{s_2-s_1}{\beta}}\right]^{-\beta}$$

- $s_1 = 2.36\pm0.05$, $s_2 = 3.1\pm0.1$ (3.5 ± 0.1) $p_{br} = 239\pm74$ (22 ± 8) GeV c^{-1} (for IC 443)
- Below the break: proton spectrum softer than electron spectrum ($s_{1,e} = 1.72$)
- Reason for high-energy break not fully understood
- CR efficiency 1-4%. Strongly depends on assumed density

Further supporting evidence

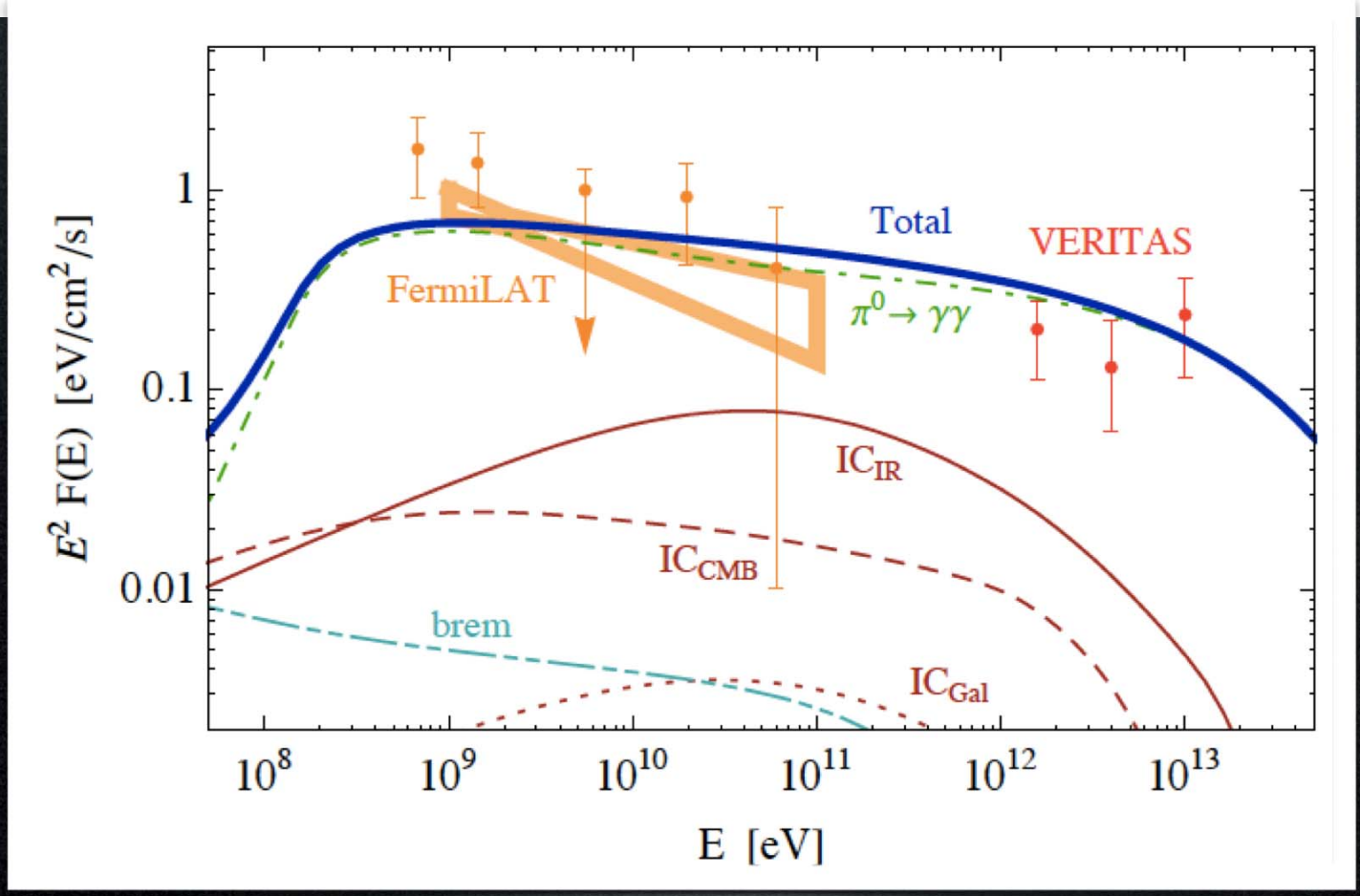
Daniel Castro, Patrick Slane, Donald C. Ellison, and Daniel J. Patnaude



- In CTB 109, Adding thermal X-ray emission to modeling can break degeneracy between emission scenarios

The unequivocal evidence of hadron acceleration in Tycho's Supernova Remnant

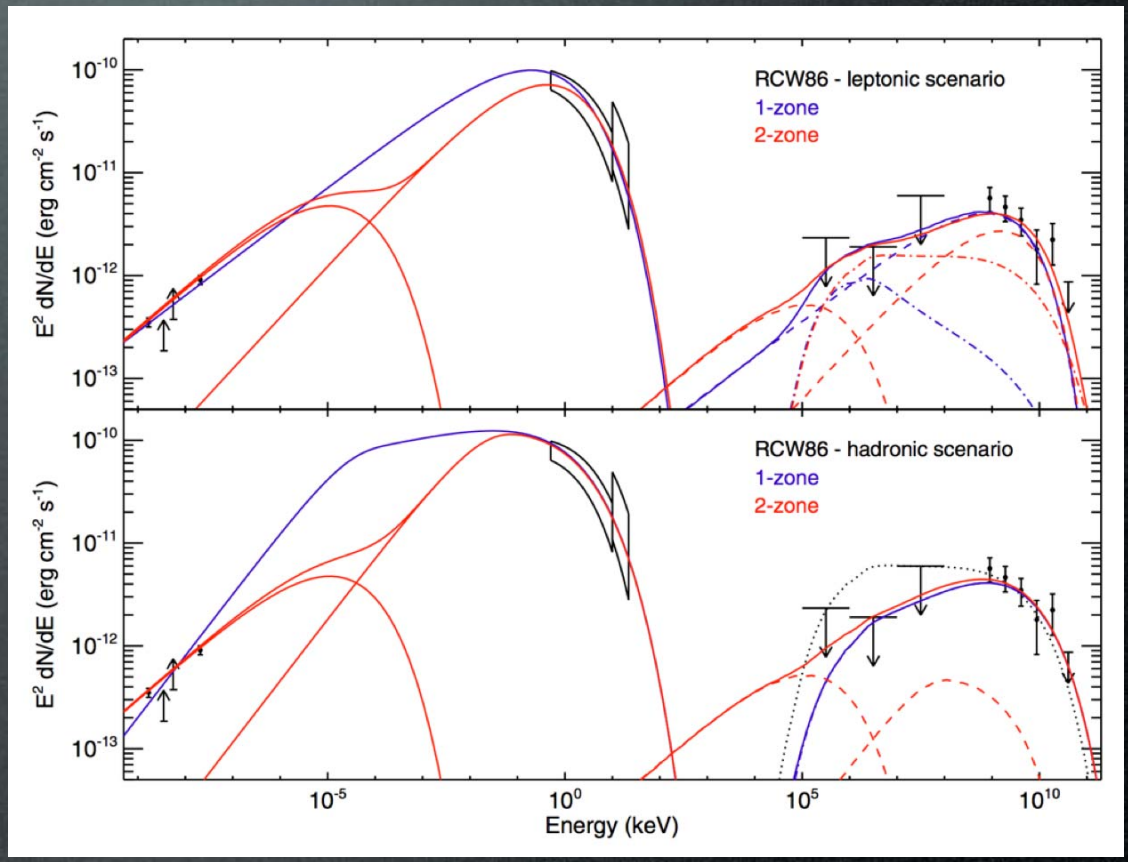
G. Morlino[1⋆], D. Caprioli[1]†,
[1] *INAF-Osservatorio Astrofisico di Arcetri, Largo E. Fermi, 5, 50125, Firenze, Italy*



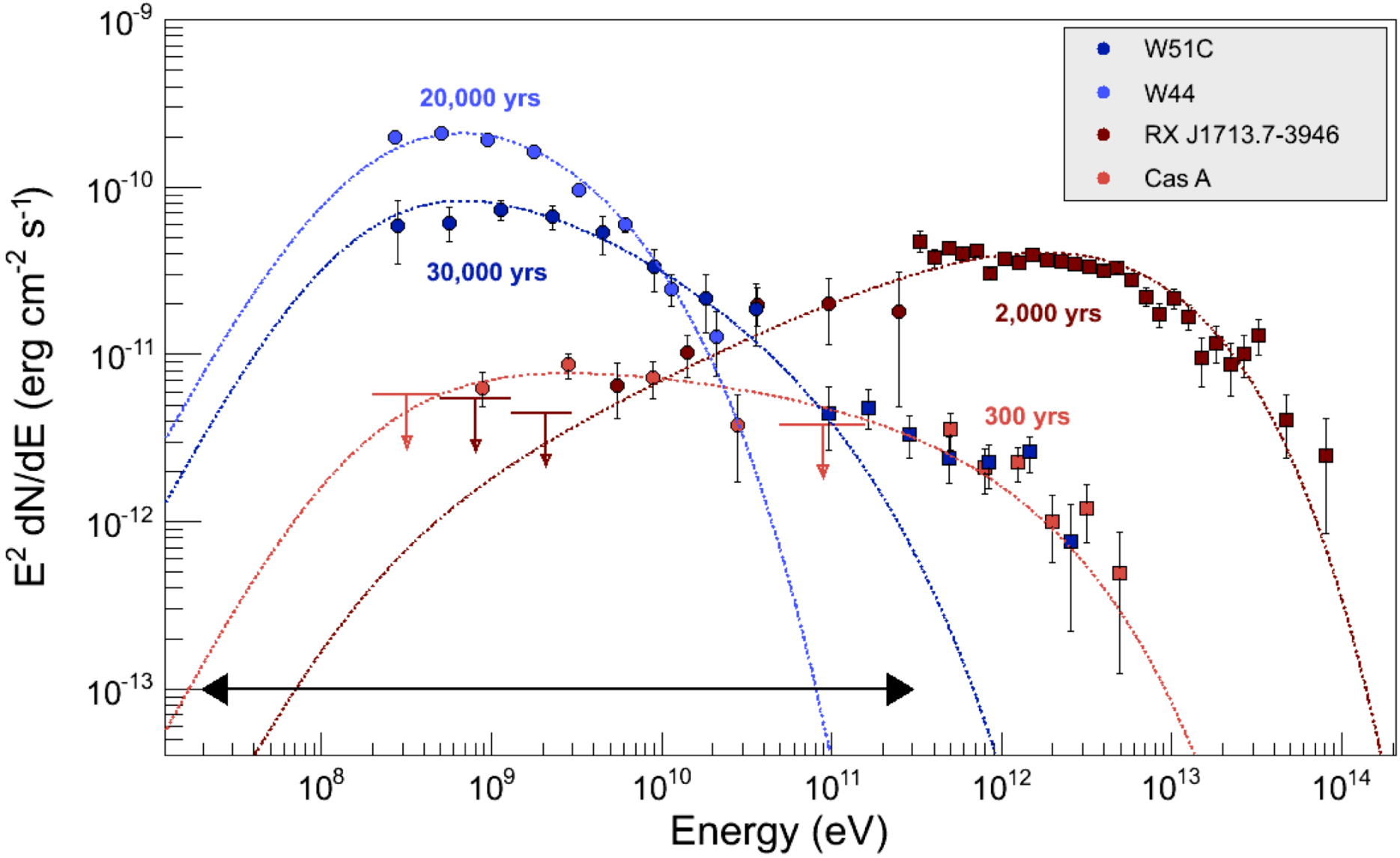
E_{max} = 500 TeV

Next step: constrain cosmic-ray efficiency

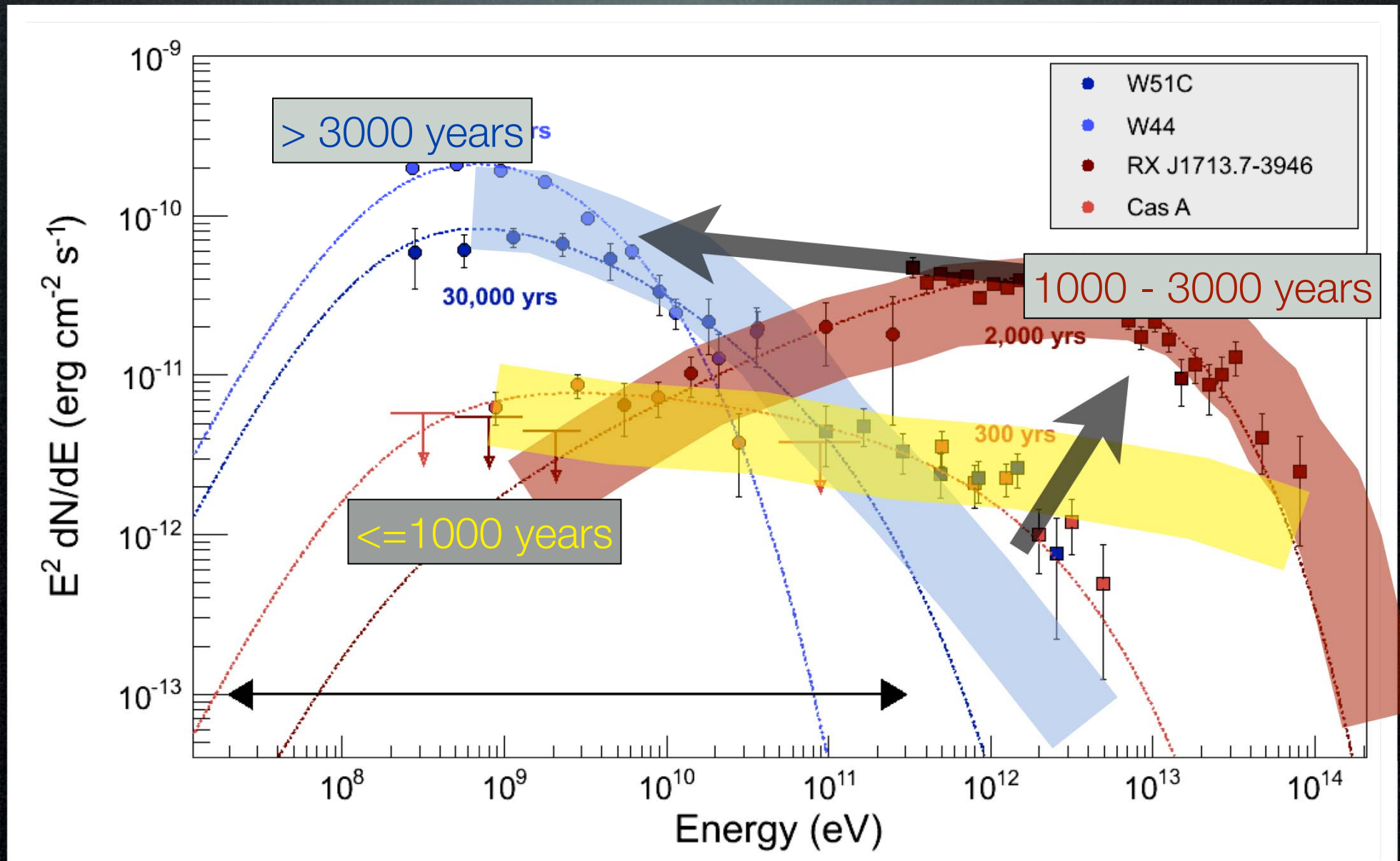
- So far done individually
- E.g. RCW 86
- Absence of signal allows to put very stringent limits on CR efficiency (<5%)



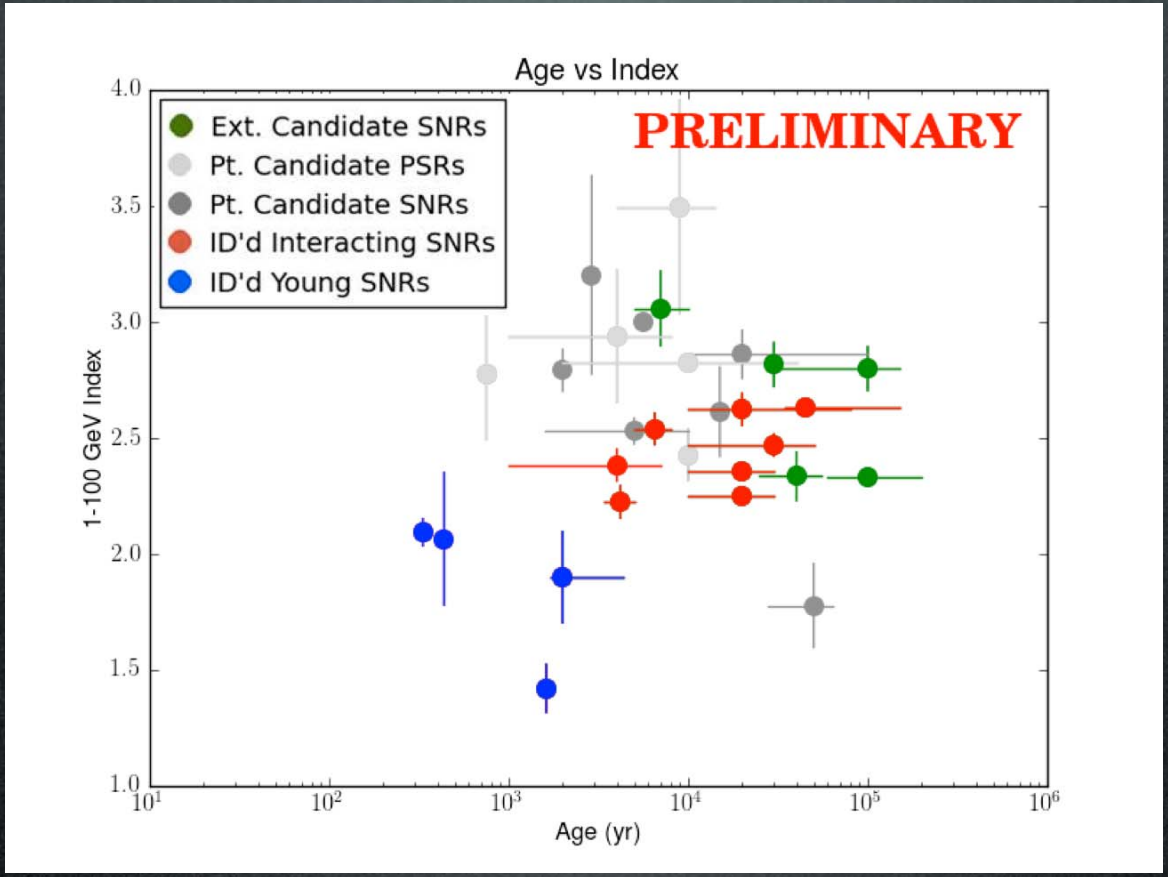
Evolution of emission



Evolution of emission



The population of SNRs

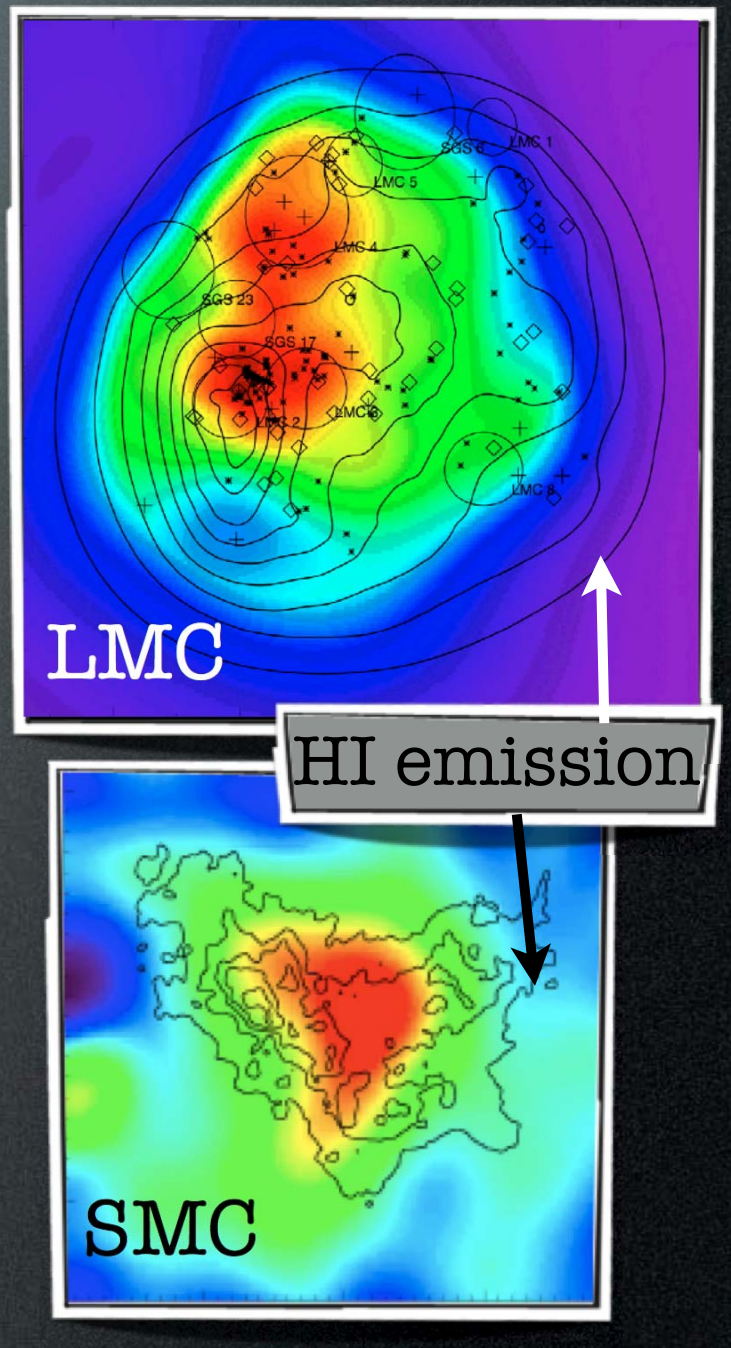


- Evolved and interacting SNRs tend to be more luminous than young SNRs
- Young SNRs tend to have harder spectra

Cosmic rays in other Galaxies

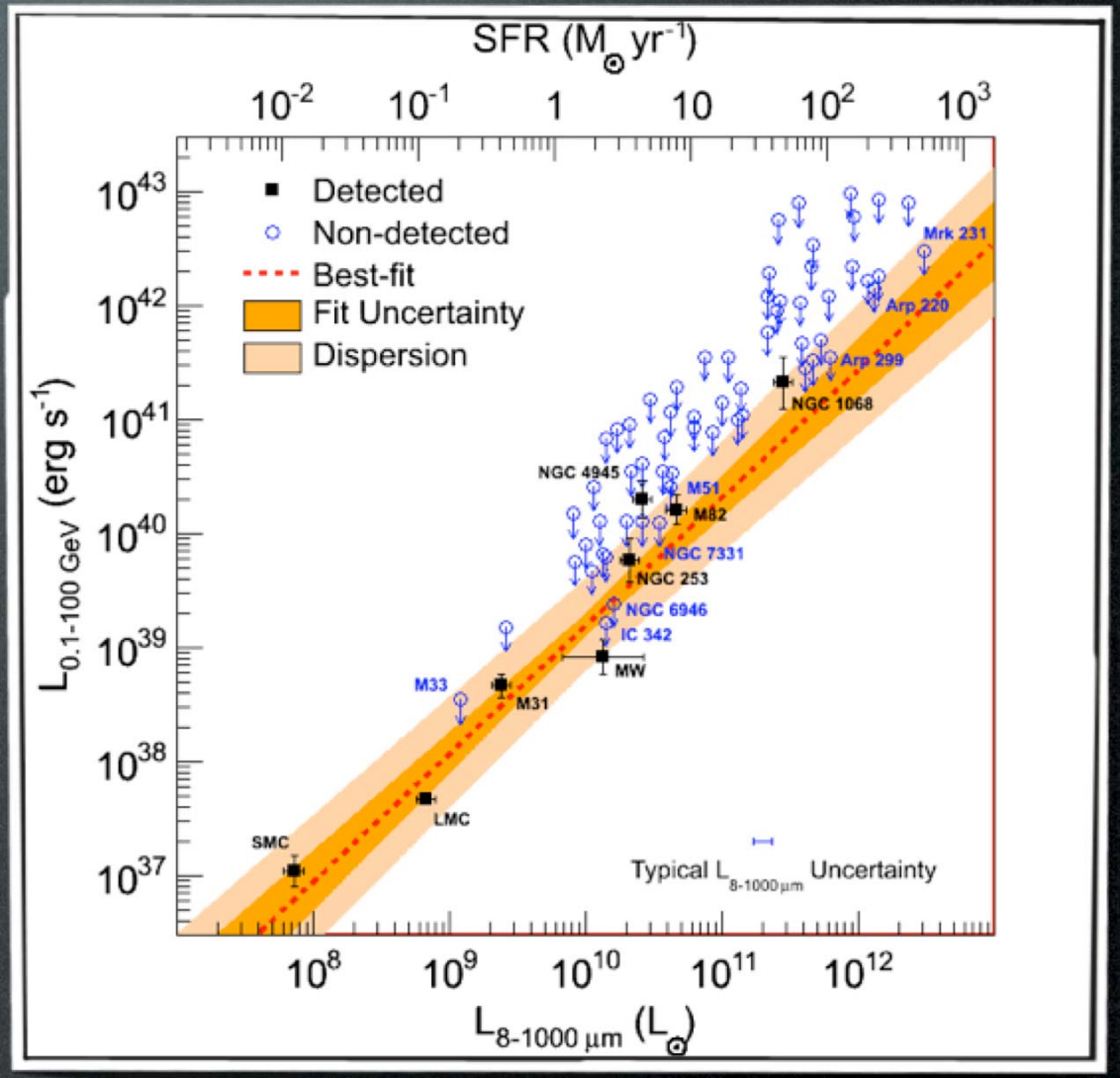
- Diffuse emission similar to our own Galaxy observable for close-by galaxies, or those with enhanced star-formation
- Detection of e.g. M82, NGC 253, SMC, LMC, M31
- EGRET: CRs < 10^{15} are galactic
- Fermi-LAT: image CR propagation in nearby Galaxies

Abdo et al. 2010



Other Galaxies

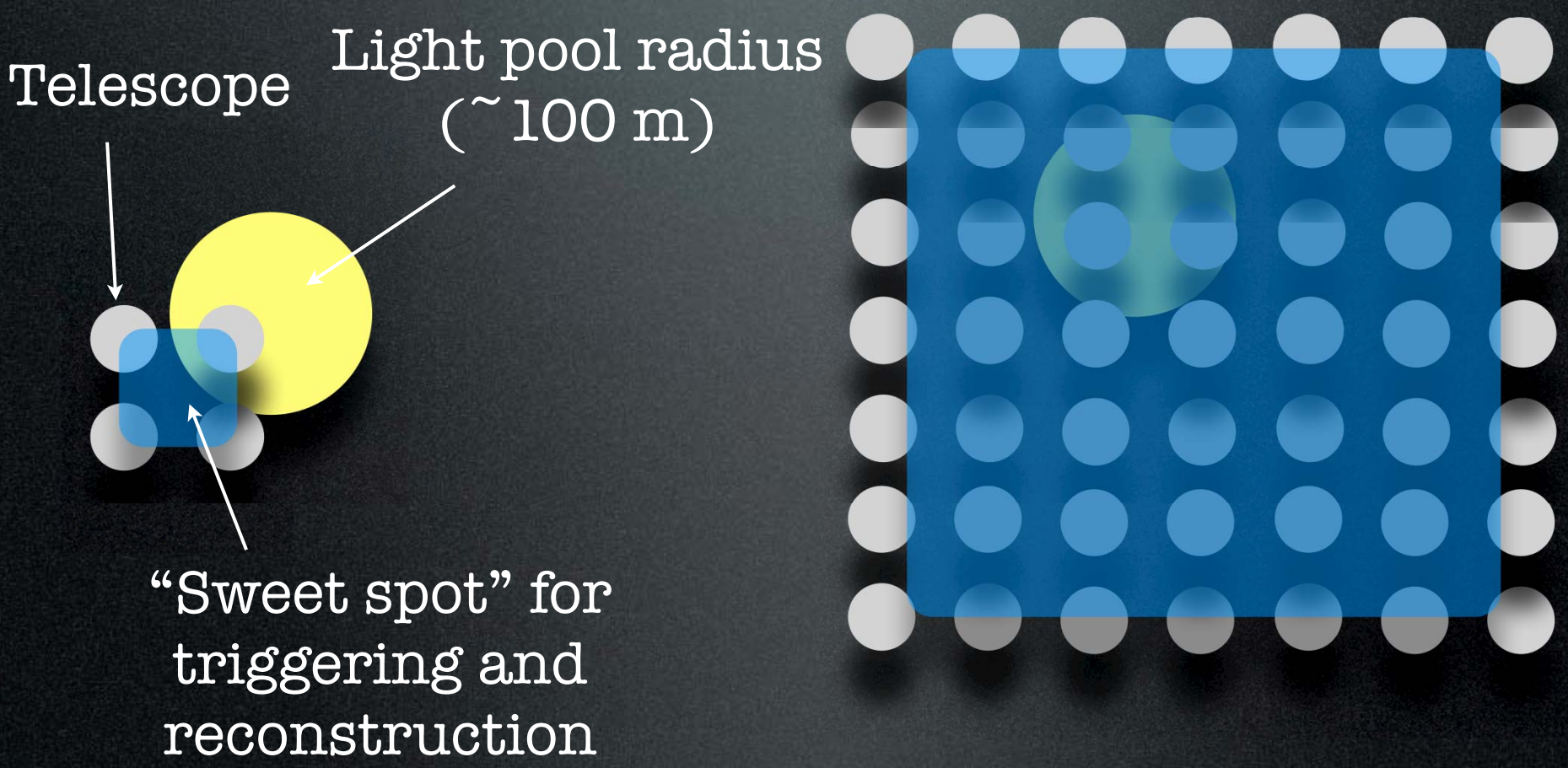
- Start to see trend of correlation between GeV γ-ray luminosity and Star formation
- Suggest that CR density is related to star-formation
- Important to estimate contribution of star-forming galaxies to Isotropic diffuse emission
- And possibly the star-formation history of the Universe ...



CTA

The concept of CTA

- Fraction of “contained events” significantly increases

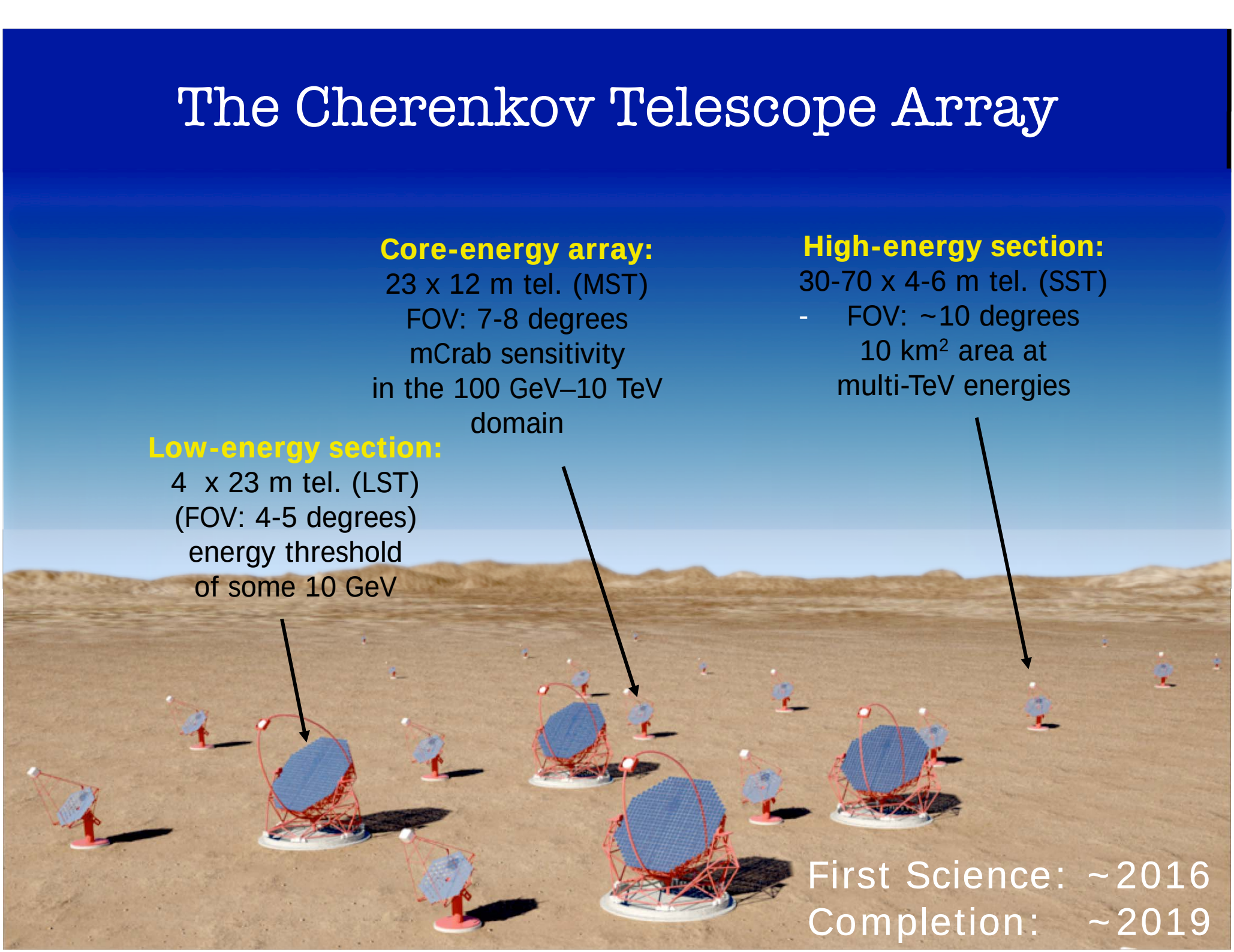


The Cherenkov Telescope Array

Core-energy array:
23 x 12 m tel. (MST)
FOV: 7-8 degrees
mCrab sensitivity
in the 100 GeV–10 TeV
domain

High-energy section:
30-70 x 4-6 m tel. (SST)
- FOV: ~10 degrees
10 km^2 area at
multi-TeV energies

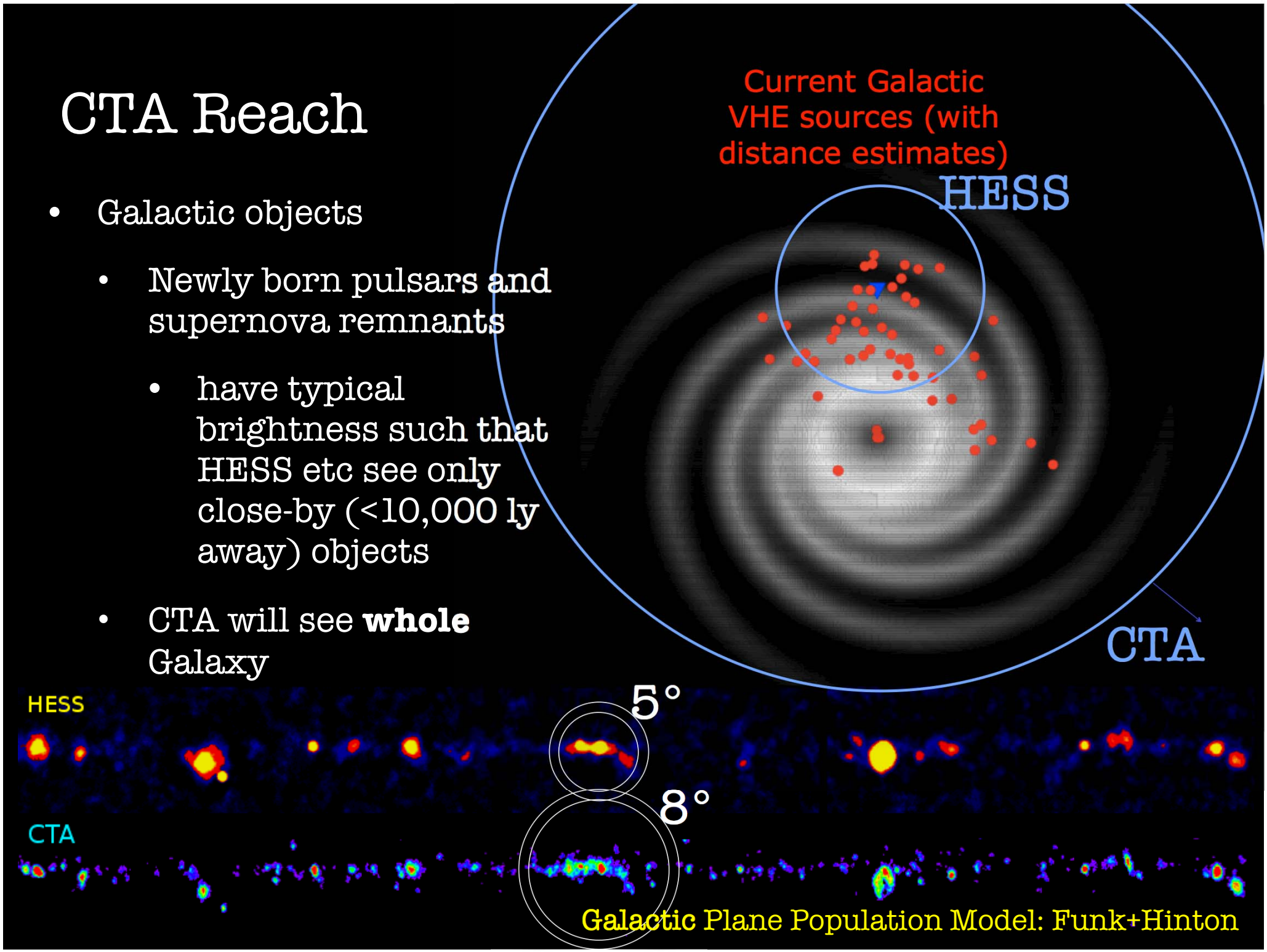
Low-energy section:
4 x 23 m tel. (LST)
(FOV: 4-5 degrees)
energy threshold
of some 10 GeV



First Science: ~2016
Completion: ~2019

CTA Reach

- Galactic objects
  - Newly born pulsars and supernova remnants
    - have typical brightness such that HESS etc see only close-by (<10,000 ly away) objects
  - CTA will see **whole** Galaxy



Summary

- Demonstration that SNRs accelerate cosmic rays
- Observing cosmic ray propagation in our and in nearby galaxies
- Next step: constrain CR efficiencies in population of galactic SNRs
- CTA: determine maximum energy, exquisite angular resolution will enhance our understanding of shock acceleration.